UNITED STATES MERCHANT MARINE ACADEMY

A STUDY OF THE UTILIZATION OF TRACTOR TUGS TO AID SHIPHANDLING IN CHARLESTON HARBOR

A RESEARCH ANALYSIS SUBMITTED TO

THE FACULTY OF THE DEPARTMENT OF MARINE TRANSPORTATION

IN CANDIDACY FOR THE DESIGNATION AS

KINGS POINT SCHOLAR

BY

MIDN STEPHEN RUSSELL SMITH, 1/C

KINGS POINT, NEW YORK

6 MAY, 1997

The great ocean of truth lay all undiscovered before me.

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8 Aug 97

POC: MIDN Stephen Russell
United States Merchant Marine Academy
Kings Point, New York

The great ocean of truth lay all undiscovered before me.
-Sir Isaac Newton

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ACKNOWLEDGMENTS

I would like to extend my greatest thanks to Commander Craig Flinn, U.S. Maritime Service, Mr. Ted Haendel, and Dr. Jane Brickman for their guidance and support as my

Service, Mr. Ted Haendel, and Dr. Jane Brickman for their guidance and support as my advisors over the past year of study. Without their knowledge and expertise this would not have been possible. Additionally, thanks to Bay and Delta Towing, the Charleston Branch Pilots, Edison Chouest Offshore, and White Stack Maritime for the hospitality extended to me while working with them as an intern.

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ABSTRACT

The use of tractor tugs throughout the United States for shiphandling and escort work has been a growing factor over the past several years. The West Coast has been on the leading edge in the use of these boats for tanker escort and ship assist work since the early 1980s. Across the country the construction rate is now approaching ten new buildings a year and there are few signs of slowing. On

construction rate is now approaching ten new buildings a year and there are few signs of slowing. On the East Coast, however, tug companies have generally failed to follow in the same direction as Pacific Coast tug owners, such as Foss Maritime, Crowley Marine, and SeaSpan. Many East Coast towing companies believe that the equipment currently in use is satisfactory for the work required. It is also a general consensus that the cost of purchasing a new advanced tug is unwarranted by current demand.

The Port of Charleston, South Carolina shares this same common problem with other East Coast ports such as Norfolk, Savannah, and New York. The intent of this study is to determine a possible solution for the Port of Charleston of how best to handle ships of increasing size safely, in a manner which is least expensive for the operation of the port as a whole. Currently, larger container vessels calling on the port's North Charleston Terminal are restricted in their transit times to the periods of flood tide only. In the near future more traffic will pass through this same area as the State Ports Authority projects a new terminal to be built. Additionally, an increased number of private terminals will be increasing overall vessel calls. A suggestion will be made for the best action to take considering the proper application of tractor tugs and their specialized operating modes. This suggestion will be based on increasing the safety and efficiency of vessel transits in Charleston Harbor, while developing the least incurred cost to the tug companies, the Port of Charleston, and its customers.

Aspects of study will include: covering views of the State Ports Authority, tug boat companies, shipping companies, the harbor pilots, and the safety of the harbor itself as an environmental body. Key points that will be examined from an objective view will include: evaluation of the adequacy of conventional tugs of various sizes and configurations currently in use, an analysis of Charleston Harbor and its projected growth patterns to define the ship assist needs of the future, the definition and comparison of existing tractor tug designs, propulsion available, suited applications, and the methodology of proper utilization of these tugs to their fullest potential. The study also will include a discussion regarding the cost of building and operating the vessel, the possibility of a short term answer by leasing or chartering, training required for the boat operators and the pilots, and lastly, the implementation of such a tug within Charleston Harbor.

Part I: Port Description and Facilities

Charleston Harbor is a modern port and intermodal transportation hub, shipping and receiving bulk, breakbulk, containerized and other cargoes from around the world. The harbor is a tidal estuary approximately 14 miles square in area, situated midway along South Carolina's coast. As part of the Atlantic Coastal Plain, winding rivers, wetlands, low-lying peninsulas and islands characterize Charleston Harbor, which is formed by confluence of the Ashley, Cooper, and Wando Rivers.

Charleston is the largest and most important seaport in South Carolina. The three major container terminals, the Wando/Welch, Columbus Street, and North Charleston Terminals, combine to form the second largest container port on the East Coast and Gulf Coast of the United States. In 1994 more than 10 million short tons of waterborne commerce were moved through the harbor, two thirds of which were containerized cargoes.[1] The number of vessel calls to the State Ports Authority container facilities in 1995 totaled 1650 ships, a 33% increase over the total vessel calls in 1990. The trend for the period between 1990 and 1995 is displayed below.

Fig. 1. Trends of total vessel calls to the State Ports Authority container terminals.[2]

The major bulk exports for the port are coal, chemical products, paper, grain, heavy machinery, automobiles, wood pulp, textiles and lumber. Petroleum products, chemicals, automobiles, plywood, bauxite and non-ferrous ores are among the major import commodities.

The three South Carolina State Ports Authority (SCSPA) container facilities within the port have a combined berthing space of almost 1.5 miles, with 18 container cranes, 7 traveling bridge cranes, and 36 top-lift cranes. The North Charleston and Wando terminals only handle containerized cargo. Columbus Street terminal handles containers and roll-on roll-off (RO/RO) cargo. In addition, Columbus Street serves as the primary breakbulk facility for the port. Union Pier Terminal is the primary RO/RO cargo handling facility. Extending up the Cooper River are six privately owned

primary RO/RO cargo handling facility. Extending up the Cooper River are six privately owned petroleum facilities including Allied Terminal Wharf, Chevron Terminal Wharf, Koch Terminal Wharf, Texaco Wharf, Marathon Petroleum Co. Wharf, and Amerada Hess Corp. North Terminal. These liquid bulk terminals are essential to the petroleum industry in Charleston and the Southeast, as there are no product pipelines serving the coastal regions of South Carolina. In addition to these terminals are several other facilities: the Shipyard River Coal Terminal Wharf, Macalloy Corporation Wharf (handling ore, coke, and ferro-alloys), Allumax Terminal Wharf (handling liquid chemicals and alumina), Westvaco Corp. Wharf (which handles primarily paper products and pulp), and the SCSPA Grain Wharf that is located at the current upper limits of the federally maintained navigable channel on the Cooper River. Additionally, Amoco Co. has a wharf that receives regular barge shipments. This facility is approximately six miles above the grain facility.[3] NUCOR, a steel manufacturer, is constructing a new steel mill in Berkeley County, above the Amoco facility, which will use barges and smaller ships for transportation of imported iron carbide used as raw materials.[4]

In the three miles between the Shipyard River Coal Terminal and the Koch Terminal lies what was once the Charleston Naval Shipyard. The Naval Shipyard was decommissioned as part of the recent base closure process. However, in its place, the Strategic Logistic Mobility Base (SLMB) and the 1340th Major Port Command (a division of the Military Sealift Command) has become the primary military users of the port. The SLMB will be the home port for 18 prepositioned RO/RO style cargo ships. These vessels will be between 881' and 950' in length and will rotate in and out of the port for servicing of their cargo and other general repairs.[5]

Other than cargo, the Charleston economy relies upon tourism and recreation for a great deal of its market income. One passenger terminal is available just south of the Union Pier facility. Being one of the oldest permanent settlements in the United States, Charleston has enjoyed a prominent spot in the country's history, from the Revolutionary War to the reconstruction period. In addition to tourism, Charleston Harbor and the surrounding barrier islands, allow for recreational and commercial uses including fishing, sailing, surfing, and other water sports.

Physical Features of Charleston Harbor

Charleston Harbor lies approximately 264 miles southwest of Cape Hatteras, North Carolina and 65 miles northeast of the Savannah River. It is considered to be "one of the best harbors of refuge on the South Atlantic coast."[6] The current, federally maintained navigational channel was completed in the summer of 1991. It provides a 42 foot deep by 1000 foot wide entrance channel, extending from the 42 foot contour line of the ocean floor to the mouth of the harbor (approximately 11 miles inland). From this point the maintained channel is 40 feet deep by 600 feet wide, with few variances, continuing 16 miles up the Cooper River to a point known as Goose Creek, just north of the Ordinance Reach (which is 1400 feet wide and serves as the turning basin for the North Channel). Other extensions of the channel include the 40 foot deep channel into the Wando River, which has a length of 2.1 miles and width of 400 feet, to the Turning Basin adjacent the Wando/Welch Terminal (which has a width of 1400 feet). The most recent additions to the controlled channel were the improvements to the Shipyard River which were completed in the summer of 1996. These improvements consisted of a 38 foot deep by 300 foot wide entrance channel adjacent Daniel Island Reach and north of the Allied Terminal Wharf, and a 700 foot diameter Turning Basin A common with the Connector Channel for Shipyard River which is maintained at a 30 foot depth and 200 foot width with a 500 foot diameter Turning Basin B. All channels have a slope of four feet of increasing width for every one foot of decreasing depth.[7]

The South Channel, connecting Mount Pleasant Range with the Ashley River is a secondary navigation channel and serves primarily to connect the Inter-Coastal Waterway across Charleston Harbor from the southwest at the confluence of Wappoo Creek and the Ashley River to its continuation behind the barrier island known as Sullivans Island. The controlled width and depth varies, but is surveyed at an average depth of just over 20 feet and widths vary between 600 and 1000 feet for a length of 3.1 miles.

Channel maintenance for the 40 foot project depth requires frequent dredging of shoaling areas.

Channel maintenance for the 40 foot project depth requires frequent dredging of shoaling areas. Significant shoaling problems exist from the Wando reach to the Wando Welch Terminal, in Lower Town Creek along the Columbus Street Terminal, Shipyard River, Daniel Island Reach and Custom House Reach. The most significant shoaling problems occur along Drum Island Bend and Drum Island Reach, which require dredging nearly every six months. As stated in the Charleston Harbor Feasibility Report "in addition to the shoaling problem, this area is difficult for large, less maneuverable vessels to navigate because of the combination of the shoal, the bend - the first turn of a tight S-turn - and the currents." The annual maintenance dredging throughout the inner harbor requires the removal of approximately 1.8 million cubic yards of sediment.[8] The South Channel is no longer maintained and survey depths made in July of 1994 indicate depths approximately equal to those taken since 1977.

Channel Dimensions And Orientation In Relation To Vessel Transits

The current channel dimensions, which were completed in August 1991, were originally designed for vessels with an 810-foot length and a draft of 36 feet. Currently there are container vessels calling on the port which are 965 feet in length with an average draft of 44 feet.[9] The container trade has grown significantly since 1960 and in the year of 1994 the port experienced a growth in container traffic of over 15%. Historically vessel size was limited by the Panama Canal and its Panamax limitations. Now with dedicated trades between the East Coast of the United States and Europe, many newer vessels are limited in draft by the maximum depth of terminals on the East Coast of the United States. Nearly half of the container vessels calling in Charleston have a design draft between 37 and 38 feet. One quarter of the remaining ships have a design draft of 44 feet. These newer, deeper vessels calling on Charleston and other ports along the East Coast indicate that the limiting depths of the Atlantic Coastal Plain are not the limiting factor in vessel design. The increased draft is effectively used elsewhere along the ships' routes. However, as the older and consequently more shallow draft ships are retired from use and replaced with larger, more efficient ones, the constraints on draft will be an increasing factor. [10] Currently, draft limitations specified by the Charleston Harbor Navigational Guidelines allow for vessels approaching 40 foot draft to call on the port. The use of tidal advantage from the average 5.2 foot tidal range allows for a 4 foot clearance between the lowest point of the vessels' hull and the harbor bottom. [11] Without an increase in harbor depth, Charleston will continue to impose constraints on the larger vessels calling on the port.

On average the cost for a vessel calling on Charleston exceeds $2,000 per hour. Light-loading has been estimated to increase transportation costs by $1.00 per ton or more. The incurred costs can be substantial, with the average number of commercial vessels calling on Charleston approaching 2,000 per year. The inability to attract additional customers for the port, because of draft limitations and sailing regulations, restricts the port and its cargo handling capacities. [12]

In addition to the draft limitations that Charleston shares with other Atlantic Coastal Plain ports, there are areas of restricted maneuverability for vessels in excess of 860 feet. Throughout various portions of the main shipping channel, two-way traffic is limited due to frequent turns and alignment of reaches. Additionally, the most significant limitation is in the area between the aforementioned Hog Island Reach and Daniel Island Bend (See Fig. 2). Adverse conditions are present for safe navigation due to channel alignment, shoaling, and several currents. Under ebb current conditions the water flow from the Cooper and Wando Rivers makes the safe passage of inbound traffic over 860 feet in length quite difficult. As inbound vessels approach the turn into Drum Island Reach from Hog Island Reach the ebbing current from the Wando River strikes the starboard side of the vessel, forcing it towards the port side of the channel and Drum Island. In the area of this interaction a significant shoaling problem exists which often limits vessels to less than full channel dimensions. In conversation with several Charleston Branch Pilots regarding this turn, it was suggested that when this particular area was dredged to remove the shoal completing the turn became more simplified. However, as mentioned earlier, this is a maintenance process that is required at intervals of roughly six months. The successful completion of this turn and navigation of the Drum Island Reach is critical for the proper alignment to turn and enter Myers Bend and Daniel Island Reach. When properly set up for this turn, an inbound vessel is brought very near the Allied Oil Terminal and the risk of a possible collision with extreme consequences is possible. [13] The effects of the flood tide are considered to be less difficult to navigate

consequences is possible. [13] The effects of the flood tide are considered to be less difficult to navigate than the

Fig. 2. A topographical view of Charleston Harbor with reach and bend names, landmarks, and proposed modifications to channel structure.[14] crosscurrents of the ebb. The maximum ebb current generally aligns with the channel and on the flood tide this phasing does not usually occur.[15]

In the passage from sea up the Cooper River large vessels require a following current or a slack current to safely navigate the bends between Daniel Island and Drum Island. These vessels are required to travel at a greater rate of speed in order to maintain steerage in the strong following tidal currents. In aligning for Daniel Island Reach large vessels generally come quite close to moored tankers at the Allied Petroleum facility.

When a large vessel passes another moored vessel alongside a dock too closely, a suction effect is created. This effect, known as hydrodynamic interaction, will commonly cause the moored ship to be drawn off the dock and range on her moorings, which may part. In the case of moored tankers at the Allied facility, the additional danger of straining the cargo hoses and chicksans connected between the ship and the dock greatly increases, and with it the possibility of a marine spill. These interaction forces can be reduced significantly when passing traffic travels at slower speeds or passes at a greater distance from the moored ship. However as mentioned, higher speeds are required to maintain steerage, and the channel is at its current maximum width. [16]

Efforts To Improve Harbor Channels

Charleston is now limited by these problems of channel alignment, width, and depth, as are other ports on the East and Gulf Coast. Vessels calling on these ports are constrained by their ability to utilize the port to their full design capacity. Additionally, the increased transit time due to limited meeting and passing areas, and areas of difficult navigation, restrict the port in its ability to grow and provide greater port services. With the increase in volume of expected traffic and increased size of vessels calling on the port, a need to improve the federally maintained channel has become evident.

Charleston has made efforts to improve the channel in ways that will most benefit the port and the steamship companies which call on its cargo facilities. Recently a co-funded feasibility study was completed by the State Ports Authority and the United States Army Corps of Engineers. A plan was formulated which will improve upon the existing federally funded channel to best alleviate the problems mentioned above. This plan calls for a dredging project that will be completed at a cost of $116,639,000. The recommended plan calls specifically for the following:

- 1) The entrance channel will be modified to a width of 800 feet and a depth of 47 feet below Mean Lower Low Water from the 47-foot ocean contour transitioning over 16.3 miles inland to a 45-foot depth at the mouth of the Charleston Harbor jetties. The remaining width of the 1000-foot channel will be maintained at 42 feet to the 42-foot ocean contour.
- 2) The channel will continue at a 45-foot depth from the Charleston Harbor jetties inland to extremities of the current federally maintained channel on the Wando River and the Cooper River including turning basins at North Charleston, Wando, and Columbus Street Terminals.
- 3) The existing channel alignment of Shutes, Folly and Horse Reaches will be realigned to increase the area in which vessels may safely pass one another in this area where three short reaches currently lie together (See Fig. 3). Fig. 3. Topographical view of proposed changes to channel structure and realignment of Shutes Reach and Folly Reach.[17]
- 4) The width of the Daniel Island Reach will be increased to 875 feet wide at Myers Bend tapering back to 600 feet at Daniel Island Bend. This will serve to increase the ability of larger vessels to successfully navigate the S-turn between Hog Island Reach and Daniel Island Reach.
- 5) A new turning basin will be added to Daniel Island Reach to accommodate the proposed building of the new Daniel Island Container Terminal. (See Fig. 4).

In addition, the existing contraction dikes along the west side of Daniel Island Reach will be restored and the existing contraction dike on the west side of Daniel Island will be removed. A new contraction

and the existing contraction dike on the west side of Daniel Island will be removed. A new contraction dike will be built along the west side of Daniel Island Reach approximately 200 feet north of the U. S. Navy degaussing pier.[18]

Principally, these improvements have been planned so that deeper draft vessels will be able to take advantage of an increased channel depth, allowing a reduction in transportation costs from tidal delays. Additionally, the need for expansion was examined by looking at other ports trading with vessels calling on Charleston. Many Gulf Coast ports have a limiting depth of 40 feet. This too is the case with the Panama Canal which allows Panamax ships of 106 feet wide and 40 draft. This is a major consideration for vessels transiting to and from the Pacific Ocean. Currently, both the Pacific and Atlantic trade routes are seeing more Post-Panamax ships operating on dedicated trade routes within one region. As far as Charleston is concerned in this matter, most of the European trading ports have harbor depths exceeding any feasible consideration for channel deepening in Charleston. Therefore, with the increasing size of new ship buildings it is <u>Fig. 4. Topographical view of planed Daniel Island Terminal and channel modifications</u> as well as new turning basin.[19] crucial for an increase in depth to accommodate these vessels and attract new customers to the port, as opposed to competing directly with European ports.[20]

Economic Analysis

For an economical determination of the optimum depth to which the channel should be increased, a cost benefit analysis was completed in the feasibility study. Each project alternative (depths varying at 1-foot increments from 41 to 46-foot) was analyzed for a 50 year period from 2002 to 2052. The final benefit to cost ratio for the 45-foot channel depth of 1.88 was determinant in the selection of the optimal project depth. Additionally the National Economic Development (NED) benefits were greatest at this depth. The NED benefits are the contributions of a project to the national output of goods and services. Benefits for this project were measured in terms of reductions of delays and harbor transit times associated with this project, as well as applying vessel operating costs to the time savings.[21]

Additional savings for transiting vessels will result by aligning the Shutes/Folly Reaches to allow two-way traffic in the upper reaches of the harbor. Today, most two-way traffic meeting and passing situations are arranged to occur between the entrance channel (Fort Sumter Range) and Rebellion Reach. The current alignment of the Shutes and Folly Reaches is prohibitive to two-way traffic and may cause delays as long as two hours and average delays around one hour. When large ships transit this area of the harbor, no other vessels can safely pass that vessel. Thus outbound vessels must delay their departure from a terminal for an inbound vessel to clear the Shutes/Folly Reaches. These delays result in an increased expense for the shipping company. The alignment of these reaches will allow two-way traffic for an additional 1.5 miles of the main channel. Upriver of this point two-way traffic is unfeasible because of the two Highway 17 Bridges, shoaling problems, and the short reach lengths and frequent bends of the reaches of the Cooper River.[22]

Farther up river, the channel modifications were planned to help solve problems of navigability incurred by shoaling, short reaches and strong currents. As mentioned earlier, the navigational problems incurred by vessels of greater than 860 feet in length are a primary concern for the port. The increase in width of the Myers Bend and Daniel Island Reach junction was planned so that large ships (950 feet) would be capable of safely transiting this area under all tidal current conditions, completing their turn, and maintain adequate clearance between moored vessels at the Allied facility and the proposed Daniel Island Terminal. Initially, the changes for this section of the federally maintained channel were contested because of the location of the proposed container terminal (which will be addressed later). The final proposal was made to allow for the proposed terminal, but does not depend solely on operation of such harbor improvements. The planned changes have expanded the channel to the east, since the Allied Petroleum Terminal is the limiting factor to the west. The increased width at the junction of Drum Island Reach, Myers Bend, and Daniel Island Reach were necessary for safe navigation in these parts. The proposed terminal location was first placed to within 125 feet of the existing channel, but has since been located farther up river to facilitate a reduced interaction between passing ships and ships conducting cargo operations. The primary concern for this section of the channel will be the interaction effects of increased traffic and number of vessels expected to be moored in this area.[23] With the completion of the proposed Daniel Island Terminal a new contraction

moored in this area.[23] With the completion of the proposed Daniel Island Terminal a new contraction dike will be placed up river of the location, as well as the additional construction of a 1,400 by 1,400 foot turning basin. Without this turning basin, ships calling on the planned terminal would be forced to travel 6.0 miles farther up river to the Ordinance Reach turning basin and then 6.0 miles back to the Daniel Island Terminal.

Environmental Analysis

Other than economic benefits, the environmental impacts of this proposed project were of concern. As a tidal estuary Charleston Harbor is fed by the Ashley, Cooper, and Wando rivers, forming a total of over 25,000 acres of regularly flooded marsh land. Along with this zone is the high marsh, which thrives above mean high water, and brackish water marshes occurring in a transition zone between freshwater and saltwater areas. These wetland areas provide an essential ecosystem for spawning, nursing and feeding shellfish, finfish, and sport fish species. Waterfowl and other wildlife including wading birds, shorebirds, marsh rabbits, otters, and minks are also dependent upon these wetlands. The inter-tidal flats are the primary habitat for the American oyster, which builds large oyster reefs, providing an additional habitat and feeding ground for other species.

The fisheries and shellfish resources of Charleston typically contain commercially and recreationally valuable fish like flounder, red drum, spotted sea trout, and bluefish. Charleston Harbor is also used as a migratory ground for American shad, striped bass, and several species of sturgeon. The harbor supports a large shrimp and blue crab population which is harvested both commercially and recreationally. The shrimp harvesting industry in South Carolina is the largest commercial fishery, harvesting 3.24 million pounds worth almost 12 million dollars. This contributed to approximately 20% of the state's harvest. [24]

Overall there are several species of both plant and animal life found in Charleston that are considered endangered or threatened. Among the most likely to be affected by the proposed channel improvements include the West Indian manatee, Kemp's ridley sea turtle, Loggerhead sea turtle, Leatherback sea turtle, Green sea turtle, and the Hawksbill sea turtle. The potential for impacts upon these species is possible with the hopper dredging method that is proposed for the construction of channel improvements. Specialized equipment (such as turtle excluder devices), monitoring by trained observers, and a dredging window between November 1 and May 31 allows for a reduced threat. Also hydraulic dredging (pipeline) will be used to remove harder bottom material and during the period when hopper dredges may not be used.

The hydraulic dredging process promotes significant short-term impacts on benthic (bottom dwelling) organisms such as polychaete worms, periwinkle snails, fiddler crabs and other invertebrates. These organisms will be displaced in the inland areas more so than in the waters seaward of the jetties. The impact is considered to be minor however, as the organisms will return to the disrupted area in a short period of time.

Overall, the known unavoidable adverse impacts on the environment will include a temporary increase in air and noise pollution during the construction process, and an increase in the turbidity of the water at the dredging site and the offshore disposal site. With the construction of new dikes it is expected that Spartina marsh grass will be impacted, like the benthic organisms however, it will quickly return. The proposed project was found "not to constitute a major Federal action" which would significantly affect the human environment and therefore an Environmental Impact Statement is not required.[25]

Expansion Of Port Facilities

To accompany the planed changes to increase areas of safe navigation for larger ships transiting Charleston Harbor, the South Carolina State Ports Authority has made plans for the expansion of its port facilities. Land on Daniel Island (800 acres) was purchased in 1992 at a cost of $12 million. This plot provides 20,000 feet of waterfront access for the development of fourth container terminal that will be constructed in several stages. Ultimately the proposed Daniel Island Terminal will have a capacity of 25 million tons with seven 1000 foot berths. Initially the terminal is to be constructed with

capacity of 25 million tons with seven 1000 foot berths. Initially the terminal is to be constructed with two 1,000 foot berthing spaces to be served by six post-Panamax gantry cranes. This initial phase of construction is planned to be completed by 2003. The total project is scheduled over a period of 15 to 20 years, being complete by 2015. The construction of berthing spaces is to be made in conjunction with the dredging of the planned 1400 foot turning basin so that overall costs may be reduced.[26]

Changes In Shiphandling

By changing the dimensions and channel structure of Charleston Harbor as proposed by the U.S. Army Corps of Engineers, the likelihood of a safe and efficient vessel transit will greatly increase. The channel design proposed has taken into consideration the anticipated growth in vessel size that will come with the increased channel depth and width. With the growth in size of vessels calling on Charleston, there is also a staggering anticipated growth in the number of vessels calling on the port. The increase in the size and numbers of vessels transiting Charleston Harbor will more frequently challenge safe shiphandling in the port. The newest generation of container ship, such as the Maersk Lines Limited M.S. Regina Maersk, carries over 6000 twenty foot equivalent containers, measures 1,043 feet in length, 138 feet in breadth, and has a draft approaching 45 feet. These large ships will make very few port calls, and will depend on the fastest possible turn around times to attain the highest profit. The proposed changes to the channel of Charleston Harbor will allow the State Ports Authority to market Charleston as one of the possible hub ports for these super container ships.

The changes to the channel proposed by the U.S. Army Corps of Engineers represent one solution to problems encountered in the handling of larger ships in Charleston Harbor. In trial simulations conducted at the Waterways Experimental Station, the proposed channel changes were tested with a simulated ship length of 950', and a draft of 45 feet. The trials were conducted, as mentioned above, at all stages of the tide so that the effects of the flood and ebb current could be examined. In many of the trial runs the ships being maneuvered through the difficult turn of Drum Island Reach, Myers Bend, and Daniel Island Reach left the channel. Another interesting note regarding the maneuvering of the ships through this turn is that most of the pilots used continuous full rudder to safely navigate through the turn.[27]

As the number of vessel calls grows, and the average size of the vessels calling grows, safe vessel transit becomes a major concern. By aligning turns in the channel and widening bends the likelihood of an incident free transit increases. A major concern still exists, however, regarding the maximum size limitation for which a ship can safely maneuver through a given turn in a channel. By applying external forces, through the use of tugboats for example, the maximum size of a vessel which may be safely navigated through a given turn increases greatly.

The higher speeds necessary for a ship to navigate safely through Charleston Harbor make the common tug ineffective for assisting a ship. An innovation in tug propulsion technology has created a new perspective for shiphandling. This new design allows a tug to interact with a ship at much higher speeds, often as high as 12 knots. By doing so, this tug effectively assists a ship in normal maneuvering, and can be used to safely control a ship which has been stricken by a steering or propulsion casualty. These highly maneuverable tugs, known as tractors, are also superior to conventional tugboats in ship docking work.

Tractor tugs have been used widely throughout Europe and to a lesser extent in the United States. The tractor tugs most common application in the United States is in tank ship escort work on the Pacific Coast, primarily for the purpose of casualty prevention. Commonly, when escorting ships, the tugs role is inactive until a casualty occurs. In Charleston the concern is not for tanker escort, but instead for the safe and timely passage of large container ships. If the tug's role were reversed, so that it was used as an active shiphandling aid throughout the transit, vessel movement safety and possibly increased vessel transit efficiency would result.

With the combination of the proposed changes to channel structure in Charleston Harbor and the application of specialized tugs, safe vessel transits will be maintained as the size of transiting ships increases. The continued excellent safety record of the port will thus serve to promote the growth and development of maritime commerce.

development of maritime commerce.

The choice to use a tractor tug is not a simple one unfortunately. There are many factors to consider before such a specialized tug may be placed into service. Two major propulsion types exist for these tugs, as well as two completely different hull designs, all with individual benefits and drawbacks. The greatest concern, however, is not performance of one design over the other. As in any competitive market, the cost of building and placing into service one of these new tugs is extremely important. Only after a careful analysis of all aspects of the tractor tug is complete, can a proper decision be made.

Part II: Shiphandling With Tugs

Throughout the ports of the world, one will find tug boats used to maneuver ships in and out of port. Ship assist work has been the primary occupation of tugs since the "great age of sail." By the 1850's the steam tug was seen throughout the world's major ports. It could easily be said that without the tugboat, the increasing size of sailing ships could not be accomplished. Before the advent of the tugboat, sailing ships had to be warped (heaved by lines to the dock), kedged (heaving a small anchor thrown over the side to move the ship), or brought alongside the dock by pulling boats. The following description by George H. Reid[28] aptly describes the application of tugs before the 20th century, "The big square-riggers were most at ease on the high seas. When crossing the bar or navigating in confined waters, they fared best secured to the end of some tug's hawser."

Fig. 5. The large container vessel pictured here requires several conventional tugs to maneuver it safely in port.[29]

As in the account of the early days of shiphandling, today the same words still apply. Many modern ships are equipped with bow and stern thrusters which allow them the ability to come along side the dock without the aid of tugs. However, with the growing size of ships calling on our ports, the need for a tug is more evident than ever before. In most ports, as in Charleston, a requirement exists to have at least one tug standing by simply for safety measures. However, a ship will usually employ several tugs to assist in docking and undocking. These tugs work by means of making fast a line to the ship in order to hold the tug in place and provide a rigid connection for pulling on the ship as it comes along side the dock. The majority of this work is done with minimal headway on the ship, usually under 3 knots. An oversimplified function of the tug today is either to push, pull or lay along side the ship passively. Reid describes the tugs functions as being:

> to assist the vessel to steer, to turn the vessel, to move it laterally, or to hold it in position while heaving up or letting go its mooring lines. In addition the tug may be required to check a vessel's way (ahead, astern, or sideways), brake a vessel's sheer, slow the vessel's swing, or even physically propel the vessel.[30]

With larger ships, especially tankers, more ship assist work is being done while operating with considerable headway, often above 6 knots. This method of ship assist work has become known as escorting, which involves closely following the ship while it is traversing the waterway. The escorting of ships in the United States was first mandated in 1975 by the state of Washington to assist in the general prevention of a hazardous tank-ship spill. All tankers over 40,000 deadweight tons transiting Puget Sound are required to be escorted by tugs having installed propulsion power of 5% of the escorted vessels deadweight tonnage.[31]

Performing a proper escort operation relies on the basic principle of having an escort vessel, a tug boat, follow a transiting ship closely and being prepared, if necessary, to control the ship by the tug's own actions. Typically the tug is made fast to the ship it is escorting by a tether line secured to the ship's stern. From this towing point, the tug should both be able to steer the ship and provide a braking force if necessary. This concept was established primarily for tanker work with the hope of reducing the number of casualties related to steering or propulsion failures resulting in collision or grounding.

Fig. 6. A Voith-Schneider propulsion unit ready for installation.[32]

Fig. 6. A Voith-Schneider propulsion unit ready for installation.[32]

To date, there is no specification regarding the required propulsion unit upon which the escorting vessel relies. The requirement for escorting a ship may be fulfilled by any tug of acceptable horsepower, seaworthiness, service speed, and reliability. However, there is an increasing inclination towards a new generation of tug boat which is not driven by conventional single or twin screw propellers. These tugs belong to a grouping of propulsion steered units called tractor tugs. The tractor tug name was adapted from the idea of the farm tractor; just as that powerful machine can turn in its own length, the tractor tugs are highly maneuverable. Tractor tugs differ from conventionally propelled tugs because of their propulsion units which provide both thrust and steering. At any point, the full engine power of the tractor tug may be directed in any direction. This ability allows for the specialized operation of these tugs at higher ship assist speeds, and hence escorting. Several different theories for propulsion are used for the propeller steered tug. One method is the Voith-Schneider cycloidal propeller which was first introduced before 1950. The cycloidal propeller system uses typically four or five air-foil shaped vanes (much like the blades of a helicopter) which rotate about a vertical axis.

Fig. 8. The typical Z-Drive installation: note the "Z" bend the propulsion shaft makes from the engine to the propeller.[33]

Fig. 7. The nozzeled, azimuth rotateable drive unit.[34]

The second system employs a conventional propeller in a right angled or Z-Drive fashion. A Z-Drive is so called because of the manner in which the propeller shaft is connected to the prime mover. The propeller shaft is just as that in an outboard motor, but the shaft angles again from the vertical shaft of the drive to the horizontal shaft of the engine.[35]

Fig. 9. The tractor configuration with noticeable skeg (A) aft and guard area (B) forward for the installation of either Voith-Schneider or Z-Drive units.[36]

Propulsion Steered Tug Configurations

No matter how the propulsion steered tug is driven, it has drive units which are arranged in one of two possible ways, either as a tractor tug or a pusher tug (today commonly know as the reverse tractor tug). The propulsion units of the tractor tug are located forward of amidships and the reverse tractor has the drive units located aft.

Fig. 10. The reverse tractor tug with extended keel (B) aft and space for the propulsion units (A) at the stern of the tug.[37] These two different placements allow for varying advantages and disadvantages of design and effectiveness based on chosen propulsion units.

Fig. 11. The diagram depicts a conventional tug coming along side a moving ship to take a line. The tug has been caught by the bow wave and will stem if control is not regained.[38]

A brief description of some major hazards of conventional towing (that which is done by conventionally propelled tugs) will make it easier to understand the advantages of the tractor and reverse tractor configurations. One of the more dangerous maneuvers in shiphandling is performed when a tug is required to take a bow line while the ship is underway. In the process of passing a tow line to the tug, the tug must come extremely close to the ship's bow. If the tug is allowed to land against the ship's side, the tug may not be able to steer its way off the ship. As a tug attempts to turn away from the ship, it may begin to slide forward, being caught directly at the bow. The only way out of this situation is to quickly back straight down away from the bow. If the tug does not pull away, it may "stem," becoming crossways ahead of the vessel and capsize.[39]

Fig. 12. Tug Fairplay I running along side the passenger liner Italia.[40]

Fig. 13. The tug Fairplay I being stemmed under the bow of the Italia.[41]

Fig. 13. The tug Fairplay I being stemmed under the bow of the Italia.[41]

In the two scenes below, the tug Fairplay I and the passenger liner Italia were proceeding through Cuxhaven roadstead. In efforts to take a bow line on the passenger ship, the captain of the Fairplay I came along side, running parallel with the ship. The tug was then moved forward to the starboard bow of the ship to be in range for passing the line. The tug was subjected to a deflecting force by the bow wave of the ship, causing the captain of the tug to have to steer towards the ship. Once the tug broke through that wave however, the resistance was lost and the tug quickly steered toward the ship. The stern came into contact with the ship, and at this moment the rudder had no controlling effect because it basically was trapped by its stern against the ship. In efforts to free the tug, full ahead power was applied, hoping to gain more rudder power and speed away from the ship. This maneuver only led to the tug advancing around the bow of the ship and capsizing. The only maneuver which could have possibly prevented this tragedy was to back away from the ship.[42]

Fig. 14. A drawing of a tug which has become girded as viewed from above.[43]

Fig. 15. A drawing of a tug being girded as viewed from the side.

Another condition in which the tug may be capsized occurs when the ship overpowers the tug, pulling it along with the towline. The tug may reach a point at which the towline is 90° to the centerline of the tug and its direction of motion. The tug may then be pulled on its side, which is called girding or tripping. In a situation where it may be noticed that the rail of the tug is dipping under the water, quick action of slacking the towline and getting away from the direction in which the tug is heeling is required. [44]

The Tractor Tug

The tractor tug gets its name from both its maneuverability and its principle operation mode of pulling the assisted ship. When doing work on a towline these boats are typically much less likely to capsize than conventional tugs doing ship work. The primary reason for this is that the propulsion units are mounted forward on the tug; typically about 1/3 of the length of the vessel from the bow. The steering force (thrust) in the tractor tug configuration is placed ahead of the pivot point (the vertical axis of a vessel, about which it will turn when moving through the water at a given speed) of the tug and the tow line force is aft of the pivot point. These offsetting forces produce a torque which will turn the vessel in the direction of the towline before the tug has a chance of tripping, possibly capsizing the tug.

Fig. 17. The diagram depicts how a tractor tug is capable of approaching the bow of a ship and thrusting away under control if caught against the ships bow.[45]

As discussed in the preceding cases describing the taking of the bow line, the tractor tug has superb safety; by locating the drive units forward, the tractor tug is able to thrust itself away and ahead of the ship if it becomes trapped against the ship. This is only possible because the drive units are located ahead of the pivot point of the tug.

Fig. 16. The drawing indicates the forces acting at the towing point of a tractor tug. The forces generated by the skeg (A) and the propulsion units (B) act through the pivot point (B) to produce the resultant steering force (Fs).[46]

Fig. 19. The graph depicts the relation between speed through the water and rudder force, direct towing force, and indirect towing forces.[47]

Fig. 18. The tractor tug seen here is producing a "rudder effect" to help turn the ship to starboard as it pulls from the center of the ship to port.[48]

An additional characteristic all tractor tugs possess is a large vertical skeg, or fin, which is placed at

An additional characteristic all tractor tugs possess is a large vertical skeg, or fin, which is placed at the stern of the tug. This skeg, shown in figure 5, provides increased directional stability which is needed when running ahead and when working on a towline. When pulling at speeds above 3 knots this fin shifts the pressure center acting on the vessel, as it moves through the water, towards the stern of the tug. With the shift of the pressure center, the skeg allows the drive units to have a greater lever arm between the point from which the tug is pulling and the point from which thrust is applied. With an increased lever arm length, greater stability and towing strength is produced. The increased pull generated by this fin increases the "rudder effect" produced by the tug being used to steer a ship at higher speeds which is required in escort towing.[49] The "rudder effect" is the resulting towline force generated by an escort tug by the use of its hull and appendages as a rudder for the ship. This maneuver is used either to help a ship through a turn or to stop a turning ship, which may have a steering failure (as shown in Fig. 18).

Fig. 20. Two tractor tugs pushing stern first on a ship.[50]

Fig. 21. The tractor tug (A) pushes stern first directly, while the conventional tug pushes bow on.[51]

The stern of the tractor tug is used for pushing purposes to maintain the greatest lever arm between the contact point of the ship and the tug and the point where thrust is applied. This provides for increased ease of control of the tug. By placing the propulsion units further from the hull of the ship being assisted, the design also minimizes the influence between the ship and the tractor's propellers.[52]

The Reverse Tractor Tug

The pusher tug, today known as the reverse tractor, is a second type of a propulsion steered tug. This scheme provides the conventional tug design with 360° of thrust. With this available thrust, the tug is capable of superior maneuverability in comparison with the conventional tug. The reverse tractor is capable of operating at the higher speeds required for ship assist work when escorting, just as the tractor configuration. The principle difference between the tractor and reverse tractor configuration is the manner in which forces are distributed on the tug when towing at higher speeds. The water flow against the hull of the tug, as opposed to the forces acting on the skeg of a tractor tug, is used to impart the required steering forces to the ship and to balance the thrust and towing forces on the tug. The same principles of balanced forces apply both to the tractor and reverse tractor when operating at towing speeds above 3 knots.

As with the tractor tug, the reverse tractor typically pushes from one end of the tug, in this case the bow. As compared to a conventional tug, when a reverse tractor needs to pull on a ship, it can effectively do so by simply applying astern thrust. These propulsion steered systems are typically more efficient than a conventional propeller operating astern. By design, the distance between the towing point, pushing point, and the thrust application point of a reverse tractor is typically greater than that of a comparable tractor tug. The lever arm, when pushing on a ship, is slightly larger for better control with a reverse tractor tug.[53]

Configurations Compared

The two propulsion steered tug configurations vary dramatically, each with its own advantages. The tractor tug configuration was originally designed by Voith-Schneider, the makers of the cycloidal propulsion unit. This configuration was originally designed for the single purpose of ship assist work. The location of the propulsion units forward of the pivot point is superior in safety and maneuverability around the bow of a ship. For a reverse tractor to accomplish the same maneuver it would likely have to run astern and then put up its bowline, or it could run ahead and rely on brute force combined with maneuverability to thrust itself away from the ship if necessary.

Fig. 22. Schottel Z-Drive control console. For a tractor configuration one would face the bow, and another would be facing the stern.[54]

Fig. 23. The two consoles above are typical of an azimuth rotateable drive tug. Fig. 17 is from the

Fig. 23. The two consoles above are typical of an azimuth rotateable drive tug. Fig. 17 is from the Kinsman Hawk, a reverse tractor tug.[55]

When working in direct contact with the ship, the two different configurations push and pull from opposite ends. The reverse tractor typically works bow on to the vessel, and thus for the operator it is convenient because all controls remain the same as when normally operating the tug. There is no need to reverse the direction he faces or to move to another steering console at the stern of the wheelhouse. With a tractor tug, all pushing and pulling is done stern on to the ship, thus the operator must reverse the direction he faces when normally running free on the tug. Typically an additional control console is available for this operation as well. In some cases, as in the Hvide tractor tug Broward, there are two steering stations as well as two sets of running lights.[56] In the tradition of tug boat races, this could prove very confusing; competitors could not tell if this tug were coming or going.

Keeping with the idea of working bow onto the vessel, the reverse tractor tug will perform escort duties in a manner which is always the most seaworthy for that tug. This keeps the free running speed roughly the same as the maximum escort speed for the tug. With a tractor tug, the highest free running speed is also attained when running ahead. However, when the tug is tethered to the ship, it runs stern first. This provides an equally stable operation platform as with the reverse tractor, but the tractor tugs' speed is lower and the course stability is reduced. Combining these factors with a tractor tug's characteristically lower after deck reduces overall seaworthiness when escorting.[57]

Fig. 24. A tractor tug runs stern first while tethered to the ship it is escorting. At higher speeds through the water the skeg of the tug is highly influenced by the propeller wash of the ship.[58]

When a tug is operating in an escort mode, it is ineffective unless it is tethered to the ship it must assist. Typically this connection is made by having the tug approach the stern of the ship while it is underway. The tug comes up to the ship and passes its line and is then secured, ready to maneuver. This operation is of little concern for the reverse tractor which is equipped with a bow winch for towing. Having the bow of the tug directly in the stream of the propeller wash has minimal effect on the tug. With a tractor tug this operation is more difficult. The configuration of the tractor tugs propulsion units forward require the tug to place its towing winch aft. To connect to the ship it is escorting, the tug must turn and run astern with the skeg directly into the propeller wash. With the large skeg forward, the course stability of the tug is greatly reduced.[59] During personal observation of two tractor configured tugs, the Delta Billie[90] and the LOOP Responder,[61] it was noted several times where the tugs were basically forced in one direction or the other when approaching the stern of the ship. The resulting maneuvering actions taken by the tug captains were swift and the incidence was actually anticipated, but nonetheless unwelcome.

Fig. 25. The direct towing mode (A) and the indirect towing mode (B) are depicted by a tractor tug.[62]

This first set of comparisons for tractor and reverse tractor are fairly rudimentary. It is an accepted fact that both configurations are highly maneuverable. The greatest controversy between configurations comes with operation at higher speeds and escort work. When escort tugs apply steering control to a moving ship, they may do so by either a direct towing maneuver or by one which uses both a steering and towing force, called indirect towing. This latter towing maneuver is typically performed only by propulsion steered tugs. The total concept of this maneuver will be discussed later in this paper.

For the purpose of strictly comparing the two tug configurations, it is necessary only to understand that the lateral resistance (that which is generated as the tug is basically dragged through the water by the ship) is essential in steering the ship in indirect towing operations. The skeg of the tractor tug provides a huge amount of lateral resistance as opposed to that which is provided simply by the hull of the tug. The drive units simply serve to keep the tug headed at an angle which will allow this skeg to interact with the water and impart a greater steering force than is possible by pulling in a direct mode.[63]

Fig. 26. The profile view depicts a trial configuration for a reverse tractor Z-Drive tug with a bulbous bow and box keel for improved hydrodynamic effect.[64]

Because of the large surface area of the skeg, the tractor tug does not rely on its hull for the lateral resistance. With a reverse tractor, however, there is no skeg. The hull is very similar to that of a conventional tug's hull, except for the area under the transom and afterpeak area where the drive units penetrate the hull. In tank trials, comparing a tractor and a similarly dimensioned reverse tractor tug, it was found that the reverse tractor had generated less lateral resistance than the tractor tug. During other identical tests, another reverse tractor, with several hull modifications below the waterline, was studied. The modifications included the addition of a box keel along the length of the tug and a bulbous bow appendage. With the addition of these two appendages on a simulated 6600 horsepower reverse tractor tug, the bollard pull (the pulling force imparted by the tug to the towline) was increased from 86 tons to 141 tons when operating in the indirect mode at 10 knots.[65] The box keel is an addition which is basically a square shaped, enlarged keel, placed along the length of the bottom of the tug. Recently the Kinsman Hawk class of tugs, built for Bay Transportation of Tampa, Florida, had box keels installed after initial construction of the first tug. The box keels are approximately 18" high by 18" wide (9" on each side of the centerline). In full scale testing, the addition greatly increased performance and course stability.[66]

With the ability of a reverse tractor tug to be built with sufficient modifications, where it is capable of generating the same lateral forces as a tractor tug, the comparisons come down to the choice of the operating company. In the business world of ship assist work, the tug companies simply want either the best product for their investment intent or the tug which has the greatest opportunity of always having a job. With this in mind the decision between a tractor tug and a reverse tractor tug lies between dedicated service to ship assist and escort work, as opposed to the diversity available with a reverse tractor.

Currently, there is an increased production and design of reverse tractor configured tugs throughout the United States. More tugs are being built for not only ship assist work, but coastal towing. In an article prepared by Alan Haig-Brown of Professional Mariner magazine, several new tugs of the reverse tractor design were compared. These tugs appeared much the same from above the waterline, but once further comparisons were made the differences in their construction began to define their multipurpose capability.

The main differences in these tugs were between their primary roles as either escort and ship assist tugs or as coastal barge tugs. The reverse tractors were basically specialized by changing their beam and draft to improve either seakeeping abilities or to improve lateral stability needed in ship assist work. Typically, a reverse tractor, which is designed primarily for barge work offshore, will have a more narrow beam, deeper draft, and a fine entrance to the water along the bow. Once the proper adjustments are made in underwater hull shape, the deck fittings are also changed. By adding heavy towing winches, the reverse tractor is capable of doing barge service work towing astern. Ship assist work can still be performed at the bow with another winch fitted forward. For any tug company, getting the most for an investment demands diversity. A tug which can do ship assist and escort work, as well as being capable of offshore towing, is highly desirable. The ability of the reverse tractor to be used in several different mission possibilities makes this tug more attractive to the investor, as opposed to the single purpose orientation of a tractor tug.[67]

When comparing the tractor design and the reverse tractor design, it must be kept in mind that not all propulsion systems are used with all tug designs. Voith-Schneider, the manufacturer of the cycloidal propulsion system, only supports the tractor configuration. The primary reason is that Voith Water Tractors are billed to be the one and only true tractor for shiphandling. To fully compare how these drive units are optimized for maneuverability and ship assist work, as opposed to offshore towing, a propulsion unit comparison must be made.

Propulsion Units

A tractor tug is most easily defined as a tug which has the capability of providing thrust through 360°. This is accomplished by one of two methods, either the Voith-Schneider propulsion system, or by azimuth-rotateable thrusters, commonly known as Z-Drives. Additionally, different operating modes, unavailable to conventional tugs, may be used to define a distinction between a tractor tug and a highly

unavailable to conventional tugs, may be used to define a distinction between a tractor tug and a highly maneuverable conventional tug.

Cycloidal Propulsion

The original concept of cycloidal propulsion came in 1926 from an Austrian engineer. Ernest Schneider developed an idea to create a feathered-drive propulsion system that would allow a vessel to handle itself with equal ease operating ahead, astern, or traversing sideways. Mr. Schneider did not have the money to produce the new propulsion system, so he presented the idea to Voith, a German steel manufacturer. The merger between Ernest Schneider and Voith resulted in the building of a prototype motor launch two years later.[68] This small motor launch was propelled by one Voith-Schneider propeller, and operated on Lake Constance. The vessel moved ahead, astern, sideways, and even turned on its own axis, without a rudder, just by control of the propeller blade movement.[69] The prototype for the first Voith Water Tractor was built in 1951. The Voith Tractor Biennia was fitted with a single 115 horse power engine coupled to one small drive unit. From this prototype it was hoped that a series of tugs with the proper dimensions, fitted with the ideal propeller size and input power, would be developed. The need for diversity, however, limited the simplification of design.[70]

Fig. 27. The Biennia, built in 1951 was the first prototype Voith-Schneider propelled water tractor. It was fitted with a single 115 horsepower drive unit.[71]

Though there is continually a need for diversification for each owner of a Voith Water Tractor, they all have similar characteristics below the waterline. The Voith-Schneider propeller consists of typically four or five vertical blades connected around the circumference of a rotor housing which is flush with the hull of the vessel. The Rotor housing rotates at a constant speed controlled by the speed of the prime mover and reduction gears, which are linked to the rotor housing by a flanged housing and a bevel gear with cyclopalloid teeth. The gear, or crown wheel, is connected to the rotor housing by a thrust plate, providing axial alignment, and the driving sleeve. A roller bearing around the driving sleeve provides radial alignment. This bearing centers the rotor casing and transmits the thrust generated by the propeller vanes through the propeller housing and into the vessel's hull.[72]

Fig. 28. The schematic depicts the internal parts of the Voith-Schneider cycloidal propulsion system.[73]

The major difference between the Voith-Schneider Propeller and a conventional screw propeller is the use of a system that controls not only magnitude but direction as well. The control of the thrust is accomplished by variation of the blade pitch, which is the angle of attack of the blade in relation to the water. The blades, which are made of a very hard nickel-steel alloy, are linked to a control rod in the center of the unit. The control rod is displaced by two hydraulic servo motors which are offset 90° from each other. The offset of the control rod is transmitted to the blades by a bell-crank lever system. The thrust is then generated at right angles to the steering center.[74] The advanced study of the kinematics of the Voith-Schneider drive becomes infinitely complex for the layman.

Fig. 29. This graph demonstrates the cycloidal path each blade makes as it rotates around the unit.[75]

The major benefits perceived from the controllable magnitude and direction are as follows: The prime mover is allowed to run at a constant rpm and direction, enabling full power to be available at all times. High input power is available and consequent response in all directions is available and essential for a ship-handling vessel.

Thrust generation is always changed from a neutral point. No thrust pulses can be generated in an undesired direction during transition. Thrust and propeller efficiency is uniform throughout 360°, allowing for maximum power to be delivered in all directions.

The generation of thrust from right angles to the axis of rotation of the propeller allows greater freedom in arrangement of propulsion units. It is possible to abandon the conventional stern propulsion

freedom in arrangement of propulsion units. It is possible to abandon the conventional stern propulsion standards and arrange the propeller at a position where the best interaction between the vessel and its towing gear is obtained for the required task.

The actual RPM of the propulsion unit is very slow, ensuring a high safety margin for the reduction of external stresses and increased service life of the unit.

The variable pitch control of the propellers allows for a stable equilibrium to exist between the towline force and the propeller thrust. This ability enables the Water Tractor to operate in a direct towing and active braking mode into a higher speed range where negative flow through the propellers would occur. The transition into any change of thrust magnitude or direction will always be done through a zero point so that no undesirable side thrust or unexpected thrust component will be present.

Fig. 30. A typical Voith-Schneider tractor tug for harbor escort and ship assist work.[76]

These characteristics allow the Voith Water Tractor the liberties of being a highly maneuverable vessel. The Water Tractor is designed with the two propeller units to be placed at the bow of the vessel where they can establish a safe equilibrium between the propeller thrust of the tug and the towline force. This is done to minimize the possibility of capsizing under all conditions. Additionally, by placing the units forward well under the hull there are no restrictions to propeller thrust; operation in all directions is permitted with minimal negative hull influence on the propellers. To protect the drive units, there is a nozzle plate below the vertical blades that is rigidly attached to the hull, providing all-round protection for the propellers from grounding from ahead or at the sides. The deep aft skeg provides additional protection against grounding in the astern direction. Because of the slow rotation speed of the vertical blades, possible blade impact velocities with debris are only about one-third as great as they would be on conventionally propelled tugs, be they azimuthing thruster or straight shaft. The base impact moment at the root of a cycloidal propeller blade would be less than half the expected blade root impact moment on a corresponding rotateable thruster system. The vertical propeller blades also are constructed of Nickel-chrome steel (similar to the material used in propellers onboard ice breakers) which makes the cycloidal propeller units unusually resistant to blade damage resulting from impact with floating debris.[77]

Azimuthing Thrusters

Fig. 31. An early prototype to the azimuthing thruster, the tug Janus by Schottel.[78]

The second propulsion system available for a tractor tug is the azimuthing thruster, or Z-Drive. This propulsion unit is available in many variations from multiple manufacture's worldwide. One of the first prototypes for this drive unit in a tractor tug configuration was the Janus, which had twin forward mounted Schottel rudder propellers. Originally the Janus, built in 1967, was fitted with twin open propellers connected to two 465 horsepower engines. The units were very similar to the early Schottel drives which were in place on barges and push boats throughout Europe. The difference was that the drives were mounted forward, in a configuration like the Voith water tractor.[79] The earliest built Z-Drive tug in the United States was built in 1977 by Gladding and Hearn. The Z-Drive is a rotateable rudder propeller very similar to an outboard motor for a power boat. The major difference is that these drives are rotateable through 360°. Typically in the case of tractor tugs, these drives are housed in kort nozzles and operate as pusher drive units. Steering is achieved by the rotation of the units in their housing.

Each propulsion unit is composed of an upper and lower housing. The upper unit is controlled by an electro-hydraulic steering system. The upper casing is composed of the parts supporting the power input shaft and pinion and the vertical drive shaft. Both of these shafts are mounted on roller bearings and tapered anti-thrust bearings. The steering gear housing has a spiral bevel gear assembly, the pinion of which is driven by one or more hydraulic pumps. The bevel gear is bolted directly to the leg and in turn to the lower unit, as the gear rotates the unit rotates to the position indicated by the control unit in the wheelhouse.[80] The lower unit gearbox, or pod, is made up of an outer housing, propeller shaft, propeller shaft seal housing and seals, roller and thrust bearings, and a nose cone. The outer housings are oil and water-tight castings of streamlined design. The leg shaft and propeller shaft form the

are oil and water-tight castings of streamlined design. The leg shaft and propeller shaft form the second right angle gear reduction. The spiral bevel gear is either keyed, bolted, or integrated with the propeller shaft. All gearing within the lower unit is accomplished by fully flooding the housing with gear oil, for which cooling is provided through the outer walls of the drive unit.

Fig. 32. The schematic depicts an azimuth rotateable thruster unit.[81]

Typically, the propeller is a single piece casting that is secured to the shaft by either a keyed or hydraulic fitting. The nozzle, which typically surrounds the propeller, is fixed to the pod and legs by struts and a mounting pad, which can be removed as needed. In different applications the nozzle size may be adjusted for both maximum speed and maximum bollard pull for a given need.[82]

An additional option available from several azimuthing thruster manufacturers is a controllable pitch propeller system. The perceived advantages here are that the engine, reduction gears, and propeller shaft are not required to stop turning or be reversed. Reversing response by blade adjustment is immediate. Idling is easily accomplished. Overall economy for the units should increase by operating at a constant speed, and required maintenance should decrease with an even, continuous operation.[83] However, on the same account, it is felt with the increased number of moving parts in a controllable pitch system, reliability is reduced. The possibility of reversing the thrust by pitch control is an obvious advantage; however, in a nozzle, reverse thrust efficiency is greatly reduced. With an azimuth rotateable system it must be considered whether the time to reverse pitch and attain a reduced thrust is more desirable than the time it takes for the units to rotate 180°. When considering idling, it is common practice for operators of Z-Drive propulsion units to face the two units towards each other; the tug will then be ready to deliver the next needed thrust. This practice is commonly done to avoid clutching the drives in and out and reduce thrust ahead or astern by angling the drives towards each other. By using controllable pitch propellers, the drives may remain engaged to the prime mover, and not produce any unwanted propeller wash from the sides of the tug.[84]

Overall, the Z-Drive units operation has several key benefits, including ease of installation, thrust performance efficiency, and cost. The use of the nozzle design over the Z-Drive propeller increases thrust performance significantly. Greater efficiency is available in a wider range through 360° than with Voith-Schneider drives. The efficiency of the ducted or shrouded Z-Drive gives an average of approximately 30 to 33 pounds force per one horsepower, as opposed to the cycloidal drives 20 to 24 pounds of force per one horsepower. A tractor tug that is fitted with Z-Drives would thus be lighter and cheaper to build, because less horsepower is required than a Voith-Schneider water tractor of equal static bollard pull.

An additional matter of efficiency is the introduction of air into the units. A vortex is created when water is not flowing by the propulsion units. The propellers tend to draw in water from around the hull. In a cycloidal unit the vortex, similar to an underwater cyclone, is vertical, spinning right to the surface of the water along the hull. With a Z-Drive the vortex is horizontal, which tends to delay drawing in air from the surface of the water. The center of the rudder propeller units are also further below the waterline, as opposed to the cycloidal units. The likelihood of drawing air into the units when the vessel is pitching and rolling is greatly reduced with a Z-Drive unit.[85]

The major and notable difference between all Z-Drive units and their comparable Voith-Schneider unit is cost. In conversation with David Hackney,[86] Aquamaster-Rauma of North America, he stated that Z-Drives are a comparable alternative to the Voith-Schneider propulsion unit, but he does not directly consider the different propulsion units in direct competition. In place of the direct competition with Voith-Schneider, there are several major manufacturers of Z-Drives, including Schottel, Niigatta, Aquamaster-Rauma, and Ulstein. Hackney feels that Aquamaster is more directly in competition with these manufacturers, which allows for a buyer's market. When compared to the Voith-Schneider drives, for which there are no identical product manufactures, the equivalent Aquamaster units are typically 25-30% cheaper. If purchasing controllable pitch units, the price difference is significantly reduced to only 5-8% cheaper. This cost difference is often a deciding factor for the production of new tractor tugs, especially for smaller companies. The fear expressed by Hackney in this situation is that manufacturers will simply sell a Z-Drive to any willing buyer. He stated one of the greatest assets of

manufacturers will simply sell a Z-Drive to any willing buyer. He stated one of the greatest assets of purchasing a Voith-Schneider unit is that Voith maintains control in determining the underwater lines of the tractor tug which are critical in achieving proper performance in escorting modes. This process is also being pursued by Aquamaster-Rauma, whose naval architects had considerable design influence in the construction of the Kinsman Hawk class of reverse-tractor tugs for Bay Transportation.

Application And Towing

Regardless of the type and placement of the propulsion units, the tractor and reverse tractor tug will always be capable of working alongside a ship just as a conventional tug would. The difference in performance, as mentioned earlier, is the way in which a tug with 360° thrust capability can operate effectively alongside a ship traveling at speeds between 3 and 12 knots or higher, depending on the running speed of the tug. At these higher speeds the escort tug must be capable of three things: stopping a ship's forward advance, initiating a turn, and stopping a turning ship.

Direct Arrest

The first method of towing to be considered when escorting a ship is direct towing or direct arrest, stopping the ship by using the power of the propulsion units. During the escort, a towline is typically placed through the center chock on the stern of the escorted ship. From that point on the ship's stern, the tug may pull on the ship and stay directly on the direction of travel, or advance, without imparting any turning moment to the ship. A conventional tug is capable of this operation at speeds up to a maximum of about 6 knots. From 0-6 knots the direct arrest capability of a Z-Drive tug is typically 1.5 times greater than the astern static bollard pull of the tug. From 6 to 8 knots the arresting forces drop off, and it is within this speed range that most screw propeller tugs (both conventional and Z-Drive) will experience overload conditions on the propellers and main engines, stalling the drives. Stalling is due to a backward, or negative, flow of water through the propellers, which acts like a brake. Direct arrest of a ship traveling at speeds over 6 knots through the water is an application very well suited for the Voith-Schneider drive units. As mentioned in the pages above, the controllable pitch blades of the cycloidal propulsion units allow effective operation in a negative flow environment.[87]

Examination of assist force capabilities for Foss Maritime's 7200 horsepower Voith-Schneider drive enhanced tractor tug determined that the greatest direct arrest towing forces on a ship came at 8 knots and diminished between that point and 12 knots. Though the arresting forces diminished, they were still significant as opposed to the likelihood of a screw propeller system becoming stalled from reverse flow. At lower speeds, around six knots, the reverse arrest force of a conventional open wheel tug of the same horse power was found to be 43% less than a cycloidal drive unit of the same horse power.[88]

Transverse Arrest

Fig. 34. A Z-Drive tug executing the transverse arrest maneuver. Note the propeller was exiting 90(to the direction of advance[89]

To counter the effects of negative flow through the propellers of an azimuthing thruster tug operating in the direct arrest mode, an alternative arrest method has been implemented. An operating mode known as "transverse arrest" has been developed and proven to be very effective in producing high braking forces. The transverse arrest mode utilizes momentum drag to slow the assisted ship to a speed where direct arrest may be applied. The transverse arrest method is accomplished by rotating the propulsion units so that each is pointed at about 90° to the centerline of the tug, thrusting outwards. From this point the engine speed is increased, also increasing the athwartship component of the propeller wash. The effect produced is similar to having two large arms dragging in the water behind a ship. It may be pictured like a swimmer gliding swiftly through the water, then sticking his arms out to the side, braking his speed immediately.

Fig. 33. Graph depicting transverse arresting forces at speeds up to 14 kts per unit horsepower as compared to arresting forces of direct(reverse) arrest.[90]

Fig. 35. The two pictures compare the location of towing point, thrust application point, and pressure center; three critical variables for dynamic arrest.[91]

At speeds above eight knots, the retarding forces produced in the transverse arrest mode exceeds those produced by reverse arrest. Also, the transverse arrest forces applied to the ship increase linearly with an increase in the ship's speed through the water. As the advance speed of the assisted ship begins dropping below eight knots the units may be rotated forward to a direct arrest position.[92]

Dynamic Arrest

Another means of stopping or slowing a ship's forward speed is through dynamic arrest. Dynamic arrest describes any means of slowing a ship by using the water flowing against the tug's hull to develop retarding forces on the towline. Both the tractor and reverse tractor tug configurations rely on the same principle of balancing two sets of forces. The required thrust for maintaining the proper orientation of the tug to the vessel being slowed or steered is dependent primarily on two factors: the distance from the towing point (where the towline first comes in contact with the tug) to the thrust point (where propulsion forces are applied), and the distance from the towing point to the pressure center (where all of the lateral forces acting on the underwater shape of the tug's hull come together). The pressure center of the tug is a variable factor depending on the angle of attack of the tug, the shape of the hull, and any appendages such as a skeg or box keel.[93]

Fig. 36. The figure depicts a reverse tractor Z-Drive tug initiating a turn.[94]

Indirect Arrest

The primary method of dynamic ship assist is called indirect arrest. This towing mode is typically used for initiating or stopping the turn of a ship, but it may also be used effectively to stop a ship's advance. Indirect towing was developed to take full advantage of the hydrodynamic drag of a tug's hull through the water and impart it to the towline and the escorted vessel. In the indirect mode, the hull of the propulsion steered tug is placed at an angle to the direction of travel of the ship. While operating in this mode, the tug's captain is only required to use the propulsion units to steer and orient the tug so that it maintains the proper angle of attack. The angle at which the tug is kept in relation to the direction of travel of the ship is the critical factor in determining how much pull is exerted on the towline. This angle of attack is typically between 30° and 60° and may be as great as 90° to the incident direction of water flow along the tug's hull. By maintaining a large angle of attack, a majority of the tug's hull is kept nearly perpendicular to the direction of travel of the assisted ship. When the hull of the tug approaches such a large incident angle, the towline forces produced exceed the forces produced in direct arrest, providing a maximum braking force for the ship. In the indirect mode, there are typically both directional forces as well as retarding forces applied.[95]

The towing force diagrams for the Foss enhanced tractor tug plot the strongest arrest forces when the tug is roughly 30° off the centerline of the ship. At this point, the tug could be oriented so that the hull is almost perpendicular to the direction of the ship's travel. The arresting pull of the 7200 horsepower tug was almost 350,000 lbs while the tanker was traveling at 10 knots. In addition to the strong arresting force created, there is a secondary steering force of almost 100,000 lbs.[96]

Fig. 37. Towing force diagram for a 7200 horsepower Voith- Schneider tractor tug. Note the maximum towing forces approaches 350,000 lbs.[97]

During normal operation, a ship under its own power may use its rudder as a brake by cycling it from side to side. This maneuver, known as slewing, is accomplished by moving the rudder from hard over to one side then hard over to the opposite side. The changes in heading of the ship slows the vessel dramatically while still allowing it to remain close to its original base course. Often this method is more practical than using astern propulsion to take way off of a ship.[98] Just as the rudder may be used to turn a ship slightly from side to side and slow its advance, the indirect mode may be applied in a

similar manner. The tug would work on one side and then switch to the opposite side to check any swing introduced to the ship.

As mentioned above, dynamic arrest operations are commonly used to steer an escorted ship. The high steering forces of the indirect mode may be applied to initiate a ship's turn or to check the ship's swing if necessary. The studies of the Foss enhanced tractor tug showed that when the towline was at an angle of approximately 65° to the direction of travel of a ship moving at 10 knots, a maximum steering force of 275,000 lbs would be produced. An increase in speed at the same angle allowed the generation of 325,000 lbs of steering force.[99]

Combination Arrest

Fig. 38. The combination arrest mode is commonly used to oppose a turn as shown above.[100]

An additional mode of operation is "combination arrest," which is very useful in stopping a ship's turn. More commonly used by azimuth drive tugs, the combination arrest mode combines both hull forces and propeller forces to stop a turning ship. It is similar to the transverse arrest in that the drive units control much of the line pull. In the combination arrest, the lateral resistance of the hull is used in combination with the propeller forces to arrest and steer a ship. This mode is particularly effective in stopping a turn, but has no real application in initiating a turn. The combination arrest mode is, however, more stable for the Z-Drive tug. It allows the propulsion units to control more of the line pull force than simply increasing the angle of attack against the direction of motion.

In comparison with the indirect mode, the combination arrest mode provides a high retarding force as well as a significant steering force. In the indirect mode the tug achieves its maximum steering force when the towline is nearly perpendicular to the direction of travel of the ship. At this point the tug may either effectively stop a ship from turning, but there is little, if any braking effect. By slowing the ship's transfer (turn of the ship) the combination arrest mode works against the ship's rudder, effectively decreasing the ships rate of turn.[101]

Operation Modes Compared

The creation of the tractor tug and its implementation into ship escort work can be easily attributed to a demand for higher transit speeds through the waters the ship must traverse. If the speed of the escorted ship was always below six knots, specialized escorting modes would not be a critical factor in the requirements of choosing an escort tug. However, the demand by steamship companies for swift transit from sea to berth sculpts shiphandling requirements to what may be less than safe conditions. When considering which type of escort vessel will be required to complete successfully a typical escort task for a given port, the benefits of each propulsion unit should be evaluated in conjunction with the expected towing modes.

Direct Arrest

The direct arrest is the basic towing mode for every tug, be it a conventional or propulsion steered tug. If the transit speed of ships calling on a given port were never to exceed six knots then it may be easily justified that a tug with steerable propulsion is not required.

For most ports, however, this is impractical because typical transit speeds are usually maintained just below or even above 10 knots. For a propulsion steered tug to be analyzed in the direct arrest, the performance of the propulsion units must be closely examined.

Fig. 39. Thrust diagram for cycloidal tractor tug.[102]

It is indisputable that for a given applied horsepower, a Z-Drive unit will provide a greater amount of static thrust than a Voith-Schneider drive. In thrust vector diagrams comparing an azimuthing propulsion unit fitted with a kort nozzle and a Voith-Schneider unit, there was a notable difference in the overall range of performance at zero speed. For the Voith-Schneider drive units, there is a

the overall range of performance at zero speed. For the Voith-Schneider drive units, there is a relatively uniform thrust distributed through 360°. The Z-Drive tug typically has a slightly reduced efficiency to either side of the tug, but ahead and astern thrust are superior to cycloidal drives.

Depending on hull design for a typical tractor tug equipped with cycloidal propulsion, forward thrust is about 85% of that produced by an open propeller conventional tug of the same horsepower. The astern thrust is expected to be 96%. The forward thrust is reduced slightly because of the resistance produced by the skeg on the after part of the hull. Thrust to either side is roughly 70% for the cycloidal drive tug; this is due to the interaction of the flow from both drive units.[103]

Fig. 40. Thrust diagram for reverse tractor Z-Drive[104]

The Z-Drive typically is capable of providing well over 100% of the thrust of a conventional open propeller tug. The ahead thrust may be as great as 125%, and astern thrust may be as high as 116% for a given reverse tractor designed tug. For a tractor tug design the astern thrust would be greatest. The reason for the decrease in efficiency between ahead and astern is again due to flow around the hull structure. For a reverse tractor tug, the hull must be designed with a sufficient cutaway to allow for water flow past the hull. Thrust to the sides has a more significant decrease in efficiency as compared to a cycloidal drive.[105]

When these figures are applied to direct arrest towing, it may quickly be determined that the greatest thrust per given horsepower comes from the nozzled propeller. This fact is not disputed until reverse flow is considered. When any vessel is towing in a reverse flow environment, the pull exerted can be as great as 1.5 times as strong as the static bollard pull. This increase in pulling force is due to the resistance of the tug's hull moving through the water. The greatest challenge for the propeller propulsion unit, as mentioned above, is reverse flow. Direct arrest becomes basically impossible at speeds above six knots for a conventional or azimuthing propeller drive unit. The cycloidal drive is capable of operating in the direct arrest mode well above six knots, but at eight knots the effectiveness of direct arrest begins to taper off, and the greater effectiveness of indirect arrest becomes apparent.

One of the principal claims of the Voith-Schneider drive is its ability to operate in reverse flow conditions. It must be noted that overloading the engines because of negative flow is not common to right angle propulsion and conventional propellers only. Voith-Schneider control stands are fitted with pitch limitation flaps, which may be used to prevent maximum pitch selection. According to the Voith Water Tractor Manoeuver Manual, "for all towing and pushing operations, limitation flaps for pitch levers have to be in position." It is clear from this statement that engine overload is very possible in any towing operation.[106]

During observations of escort operation with the 7200 horsepower LOOP Responder, it was noted on multiple occasions that the captain made a conscious effort not to go above a pitch of 8.5 (pitch range is from 0 to 10 as a maximum) when working on the towline. On the modern Voith-Schneider control stand, the pitch indicator has a red sector above the 8.5 pitch selector. On numerous occasions, engine overload alarms were signaled, and the pitch to the units had to be reduced. Even when running from offshore to the dock, full pitch was not used. Engine overload is a factor which, regardless of the propulsion unit, can quickly damage an engine.

Another limiting factor of the Voith-Schneider drive is the manner in which power applied for directional control pitch and ahead or astern thrust. The directional pitch of the vertical vane drives takes a greater percentage of applied power than the thrust pitch. If running ahead at pitch 8 and a hard turn applying a pitch 6 or 8 to either side the Voith Water Tractor will stop its forward advance and go into a very tight spin in the direction the steering pitch was changed to.[107]

Transverse Arrest

Because the problems of negative flow through a propeller cannot be countered simply by increasing the horsepower of a drive, an alternative arrest mode had to be developed for the Z-Drive equipped tractor or reverse tractor tug. The answer was the transverse arrest mode. The technical interpretation

tractor or reverse tractor tug. The answer was the transverse arrest mode. The technical interpretation of this mode cites three hydrodynamic effects that make this operation mode work. The first, a rather small effect, is the drag created by the nozzles moving through the water perpendicular to the direction of movement. Second, the propeller wash is flowing counter to the forward advance of the tug, basically creating a lot of friction between water flowing out of the drive units and the surrounding water. Lastly and most importantly is the interaction of the hull and the wash. The transverse wash creates a vacuum behind the moving hull of the tug. If it can be pictured, the wash basically makes the hull seem like it is much larger than it is. No matter how the operation is visualized, either as the swimmer sticking his arms out as above or as just mentioned, this mode is highly effective.

The pull generated by this mode is equivalent to the maximum static bollard pull when drive units are thrusting transversely at full power and the advance speed of the escorted ship is 10 knots. When the speed increases to 14 knots, the pull is approximately 140% of the maximum static bollard pull. This value varies, of course, with the drag of the hull, but is nonetheless very high.[108]

A nozzled propeller is most effective for the transverse arrest maneuver because of the way it draws water from one side of the propeller to the other. The nozzle shrouds the propeller and prevents it from being affected by water flowing past the units perpendicular to the direction of thrust. The nozzle allows the Z-Drive to have a well defined inlet and outlet to produce the large column of water necessary for the momentum drag effect.

When compared to a Voith-Schneider driven tug and a conventional tug, the increased forward movement through the water would render an open propeller or a cycloidal propeller comparatively ineffective. Additionally, it is not common for a Voith-Schneider tractor tug to be set up with individual steering controls, allowing the units to provide opposing athwartship thrust.

From personal experience, when operating a Z-Drive tug, one of the first things learned is placing the units at 90°, thrusting away from the centerline. In this position the units may be in gear, but because they are pushing towards each other the effect is neutralized. This position is very stable and considered a safety if ever the tug skipper finds himself in trouble and needing to regroup.[109]

The advantage of this mode is based upon the tug's ability to remain in line with the direction of travel of the ship. Braking forces may be applied without any incident turning moment affecting the assisted ship. Even though this operation mode appears to be the answer to problems with negative flow encountered by the azimuth-rotateable thruster, there is one major drawback. If one of the two units used to provide the transverse thrust were to drop out, either because of engine failure or by some other unforeseen cause, the tug would not be able to operate in the transverse arrest. With no transverse arrest capabilities, the tug would be forced to attempt to operate in the indirect arrest mode with one drive unit, which is highly dangerous but possible.

Indirect Arrest

The indirect mode of operation is one which requires comparison beyond what type of drive units are used. The major factor in indirect towing is the design of the tugs hull and its orientation as either a tractor or reverse tractor tug. The hydrodynamic forces generated by a tractor tug operating in the indirect mode are unquestionably higher than those generated by a comparable reverse tractor with traditional hull lines. The large fin placed at the stern of the tractor tug provides a much greater resistance area required for the indirect mode. For this reason, a tractor tug configuration is certainly superior in pure escort operation. However, because of the way in which the tractor tug is required to be configured, it is necessary for the steering force provided by the drive units to be significantly higher than those for a reverse tractor. This is all directly related to the distance between the point at which the drives are located in relation to the towing point. The tractor tug configuration has a shorter distance between the drive units and the towing point, as compared to the reverse tractor of the same length. Thus, because of the reduced distance, the effective steering lever arm of the tug is reduced, and more power is required to provide the same force as a reverse tractor of the same horsepower and length. (See Fig. 41 for a graphical explanation of the distances between related points mentioned above.)

Fig. 41. Force balance between reverse tractor and tractor tug operating in the indirect mode.[110]

If a tug's diversity of work both as an escort tug and a harbor tug dictate that it be designed as a reverse tractor, the need to add certain hull appendages such as a bulbous bow and a box keel will become evident. The addition of such appendages will be required to produce the same hydrodynamic forces as a tractor tug of equivalent length and horsepower.

By examining the two restraints on the different configuration, one can determine several critical points on escort tug design. For a reverse tractor to produce the same hydrodynamic forces as a tractor tug, and thus have the same arresting and steering ability in the indirect mode, certain hull appendages must be added. Second, due to the reduced steering moment in relation to the placement of the drives and the towing point, a higher horsepower tug would be required to produce the same towline force. As indicated in the diagram, the stern drive tug fitted with the proper appendages is capable of producing equivalent side forces (which would steer the ship) and higher towline forces with approximately 30% less applied steering force.

This principle of specialized design also relates directly to the statement above by David Hackney regarding the importance of a drive manufacturer aiding in design of the tug. The most effective hull in relation to the drives is critical for meeting the performance expectations of the tug. An effective tug can not be made by simply building a hull, dropping in drive units, and expecting it to perform as expected.

One aspect of indirect towing, which is dependent on the drive units, is the reaction time of the vessel. When operating in the indirect mode, the escort tug has been described as "a puppet on a string." The speed and momentum of a wayward ship is often beyond immediate control of the tug. The time necessary for drive units to begin thrusting in one direction or the other is critical. In this aspect, the Voith-Schneider drives have a clear advantage. The basic concept of control of Voith units with two pitch levers and a wheel make adjustment of the tug's angle of attack relatively simple. The azimuthing thruster system is controlled either by a toggle stick or by individual unit control. The toggle stick system uses a computer to determine the azimuth necessary for both units to drive the tug in the desired direction. The possibility of computer failure may leave some tug captains uneasy. The other method of steering control is by individual unit control. The throttle speed and direction control may be integrated into one unit. This requires understanding what the effects of each unit will combine to produce when applied together. The reaction time of the tug skipper and the units themselves may not be as quick as the simple system of the Voith's dual pitch control and steering wheel.

Combination Arrest

The combination arrest mode is used only when stopping the turn of a ship. This dynamic arrest mode is less dependent on the hydrodynamic forces produced by the hull of the tug than in the indirect mode. The engines of the tug are oriented so that the tug's hull is in line with the direction in which the ships stern is swinging and then the thrusters are angled so that they pull against the direction of travel of the ship and the swing of the stern.

Fig. 42. Combination arrest mode orientation for a reverse tractor tug.[111]

Fig. 43. Indirect mode applied by reverse tractor tug to oppose a turn.[112]

The value of the combination arrest is easily noticed at lower speeds of advance. In comparison tests, between indirect towing and combination arrest towing to stop the turn of a ship at 5.5 knots the combination arrest mode produced a pull of 174,000 lbs with a towline angle of 69°. The same tug operating in the indirect mode was forced to go to its maximum operating angle, 90° to the ship. At this angle the tug developed 101,000 lbs of arresting force. When a tug operating in the indirect mode approaches 90° to the ship with its towline, the forces for halting the ships turn are a maximum, but the arresting forces are minimal. As long as the ship continues to have the same forward flow of water over the rudder, the turning force produced by the rudder will not be diminished.[113]

over the rudder, the turning force produced by the rudder will not be diminished.[113]

At slower speeds (5-9 knots), the combination arrest is highly effective because it is not dependent on hydrodynamic forces acting on the hull of the tug to impart towline forces. The arresting forces come from the thrust of the engines, operating either in a direct arrest style or a transverse arrest style. The orientation of the hull produces some breaking force to decrease the effectiveness of the rudder.

Fig. 44. A tractor tug operating in the combination arrest mode to oppose a turn.[114]

Fig. 45. A tractor tug operating in the indirect mode to oppose a turn.[115]

Operation Training

For the propulsion steered tug to be effective in the utilization of its specialized towing modes, the operator must have a full understanding of the tug's capabilities. Without being able to properly execute the maneuvers described above for arresting and steering a wayward ship, the escort tug does little good to, and may actually be a hazard. The training for a propulsion steered tug captain is in many ways similar to that for any other tug captain.

When learning to drive tugs, an operator will often specialize in one particular style of tug boat and become highly proficient at its operation. In many cases a captain who learned to work a ship using a single screw tug may feel out of place when tasked to do the same job with a twin screw tug, which many may consider more maneuverable. The same circumstances exist with a propulsion steered tug. Because of their amazing maneuverability, it is often suggested that any style of boat driving ever learned need be forgotten when learning to drive a propulsion steered tug.

Voith-Schneider drive tugs have a distinct advantage in ease of operation. The arrangement of the thrust controls is very similar to a twin screw operation. Voith-Schneider tractor tug operators must often switch their orientation from looking at the bow when running free to looking astern when tethered to the ship. At first this would seem to create confusion in steering, but the simplistic control remains the same. Forward and astern thrust has no change; the controls may be either pushed or pulled in the direction you wish to go. When oriented to running stern, first pushing the thrust controls towards the stern of the tug makes it go astern, and pulling them towards the bow makes it go ahead. Steering the boat also remains simple. Because of the location of the propulsion units, the tug will pivot very close to its center, thus the operator simply turns the wheel in the direction he wishes to go. It also can be considered by the way they wish the bow to swing, thus changing the angle of attack. When working astern (as when doing any towing work), it is often best to think of the directional control as a strong thruster at the opposite end of the ship.

When first learning to drive the Voith-Schneider tug, it also must be remembered that the best way to stop an undesirable effect is not to reverse the effect, but instead go immediately to a neutral position on the thrust control and the direction control. Once at this point, the operator may regroup and correct his error.[116]

The operation of Z-Drive equipped tugs is slightly more difficult. The location of the units must always be considered because they are constantly thrusting while the units rotate. The azimuthing thruster tug may be controlled by either a single toggle stick (similar to a joy stick controlling azimuth direction) which controls both thrusters through a computer to produce the desired directional control or by dual toggle sticks for independent control (which typically control azimuth direction and engine throttle). In addition, the throttles of the engines must be controlled because most Z-Drive units are not controllable pitch as the Voith Schneider drives are.

When operating with a toggle stick, the control is just pointed in the direction which the operator wants to go and the computer swivels the units to their required position. This style of operation allows for more simplistic control of the Z-Drive tug, but there is some delay time for processing the toggle stick demand to the units. When operating each unit independently the captain must consider the effects of the two independent thrust vectors and how they will combine to control the direction and speed in which the tug will maneuver. For both systems of thruster control, the operator must

and speed in which the tug will maneuver. For both systems of thruster control, the operator must always be aware of the danger of rotating both thrusters so that the propeller wash interacts between the outlets of the units. This interaction can lead to overloading the units and damaging both the thrusters and engines.[117]

No matter which propulsion system is used, the key to safe operation of the tug depends on the experience of the operator. Voith-Schneider operators are often trained by professional instructors when first taking delivery of their new tug. Aquamaster Rauma, a prominent Z-Drive manufacturer, also has a group of professional trainers and works closely with Z-Drive tug operators throughout the world in developing new towing styles and tug designs.

Part III: Concluding Analysis

By gaining a full understanding of how the tractor or reverse tractor tug can be applied to shiphandling, an analysis of changes in shiphandling methods within Charleston Harbor may be conducted. The primary concern for the port of Charleston as a whole is safety and efficiency, both for cargo operations and vessel transits. On a cross comparison, efficient cargo operations depend on good shiphandling. The ships must arrive at the docks on time so that cargo may be worked promptly by the ordered labor. The ships transiting the harbor and near docks must also account for the speed at which they pass other ships that are alongside the dock working cargo.

These points have all been addressed in the port analysis section of this paper. Simply noting a problem, however, is not the solution. The information presented in this paper should provide insight into a possible solution, or at least a positive step towards providing the safest and most efficient manner of handling the ships calling on Charleston now and in the future.

The tugs currently operating in Charleston Harbor vary in configuration and horsepower. There are two major ship assist companies working within the port, both of which provide contracted docking services. Both companies operate single and twin screw tugs. The power of these tugs varies from 1800 to 4000 horsepower. These tugs serve the port well, aiding in the docking and undocking of almost every ship calling on the port. For the commercial tug companies, the choice of introducing a tractor or reverse tractor tug into the port is a major decision. The cost of construction and operation must be justified by the demand of the customers. In addition to demand, the company must also decide on the rate to charge for a specialized tug such as a tractor or reverse tractor. In a personal interview with Captain Tim West, Vice President of Operations for White Stack Maritime, he said "There is not a tractor tug at the end of my dock today because (the customer) says 'Yes that is a nice gadget, but we are not paying for it.' There is no need to pay a premium price for a fancier gadget. At the present time a tractor tug will cost perhaps more than waiting (for the flood tide)."[118] As long as a tug company has customers willing to wait on the stage of the tide, an immediate need for a specialized tug will not present itself.

If the immediate demand for a specialized tug were overlooked, an analysis can be made based solely on the safety and efficiency of the port. A fair decision can be made for proper tug selection by examining the facts previously presented. Trial analysis of the ship assist requirements for a ship of 950 feet in length through the Drum Island Reach - Myers Bend turn at all stages of the tide determined a bollard pull of 200,000 lbs was the force necessary to maneuver the ship through the turn. This would require a tug of roughly 6000 horsepower. Increasing the horsepower would allow for the increase in size of the expected ships in the near future and allow to err on the side of safety.

To select a tug with no regard to cost of building, which as mentioned, is the major factor for many operators, a task analysis must be completed. For Charleston Harbor the major concern is safety of the maneuvering ship. This is basically an escort criterion. The tug chosen for this job will likely be dedicated to ship assist work. The Voith Water Tractor presents itself as the immediate choice as a superior ship assist and escort tug. The cycloidal units lend themselves to a faster response time, and better adaptation to the possible conditions of reverse flow situations when working a ship. The orientation of the Voith system as a tractor tug also increases the tugs' strengths as a ship assist tug. The large skeg is vital in producing the hydrodynamic effects necessary for towing in the indirect

The large skeg is vital in producing the hydrodynamic effects necessary for towing in the indirect mode. If it were ever necessary to diversify the mission of the tug, however, it would be very difficult to effectively use the tug in offshore towing operations. Though the Voith Water Tractor may be used for barge work, it is not at all economical. The efficiency of the cycloidal blades and thrust developed is significantly less than that of any nozzeled propeller. As well for almost the entire range of thrust ability, the azimuthing thruster provides a superior thrust to horsepower ratio (See Fig. 39 &npsp; and Fig. 40).

To date there is no issue over which hull design will be incorporated with the cycloidal drive units. As mentioned earlier, Voith-Schneider maintains a major role in the design of the tugs hull structure to maximize hydrodynamic forces that will be in line with the parameters desired by the owner of the tug. The tractor design has been proven to work effectively in all conventional and specialized ship assist modes. The only mode of operation a cycloidal unit is incapable of performing, regardless of hull configuration, is transverse arrest.

If cost were never a factor in the decision of what is the best solution, providing the best service to the customer would be a simple matter indeed. However, since this analysis is an examination of a real problem, a realistic answer must be available. The companies in the United States that operate Voith-Schneider tugs have been able to do so because of a guaranteed income to pay for their investment. The typical 40% increase in cost for the Voith-Schneider propulsion system as opposed to azimuthing thrusters is a significant limitation to many builders. Foss Maritime has been the primary owner of cycloidal tugs in the United States, with a fleet of nine cycloidal tractor tugs. Crowley Marine Services has recently built two Voith-Schneider tugs, and Edison Chouest Offshore owns one. The primary purpose of these tugs is to provide a tanker escort service which is mandatory for the waters in which they work. Ship assist work for other cargo ships is secondary.

For the port of Charleston there is no requirement for the ships calling on the port to take an escort, nor are they required to use a specialized tug to transit the channel at a time other than slack or flood current. The investment by a ship assist company in a tractor or reverse tractor tug would be based solely on an attempt to gain a greater percentage of the available market share. This would be accomplished by providing the customer with the opportunity to use an advanced tool to move their ship more safely and efficiently through the harbor. The only possibility of a mandated requirement for these specialized tugs would be similar to another requirement which already exists. As mentioned in the port analysis, ships greater than 860 feet in length are required to wait until a slack or flood tide to transit the area of Hog Island-Drum Island Reach and Myers Bend. The navigational guidelines may be amended so that if a ship of such length were to transit on the ebb tide, it would be required to use a specialized tug to do so. Thus the shipping company would be offered the option of either delaying the ship for a timed transit which may cost upwards of $2,000 per hour, or employing the services of a specialized tug to assist the ship through any confining waters. The port, as a whole, may be reluctant to mandate such a requirement. If implemented, the requirement for tractor or reverse tractor to be used would in effect be mandating a possible cost increase for a vessel calling on the port.

The United States Coast Guard would be the creators of such a requirement, so the cost to the vessel is secondary to the safety of the port. It seems that such a decision would be likely, but that may not be the case. In other ports where an escort tug is required, it is not specified what type of equipment should be used. Many escorts in ports such as San Francisco are performed by large, high horsepower (6000 BHP or more), conventional tugs, as well as tractor tugs. This would be the first instance where the best available technology in a port would be required to be used. The complications of such a requirement are astounding; therefore, the conclusion of this analysis will be drawn based on the opportunity of the shipping company to employ the services of the tug company.

Because the introduction of a specialized tug into Charleston Harbor would likely first be a commercial venture before it became a required aid for shiphandling, it is probable that the tug company choosing to purchase such a boat would do so to get the most from its investment. If this is the case, the logical choice would be to select azimuthing thrusters as the propulsion platform for the tug. These drive units are fast becoming the choice of the majority of newly constructed tugs in the United States. The Z-Drive thruster provides a greater thrust per horsepower as compared to the cycloidal propulsion system. It is true that the response time for a desired thrust is slower than the

cycloidal propulsion system. It is true that the response time for a desired thrust is slower than the cycloidal drive; however, this does not noticeably reduce overall performance. The principal argument against the Z-Drive is its inability to operate in a negative water flow state through the propellers. This argument is also valid, but it must be remembered that the cycloidal propulsion unit is also susceptible to reverse flow effects at a lesser degree.

Operation modes are also highly debated, many contend that a tug equipped with azimuthing thrusters cannot safely operate in the indirect mode. Originally there was a great concern for the possibility of the tug broaching if it were to lose one of its drive units. Aquamaster-Rauma, a leading manufacturer of azimuth rotateable propulsion, has conducted tank tests and live trials and found that no significant hazards existed for the Z-Drive equipped tug. The debate over the ability of these drives to perform to expected parameters for escort work has dwindled over the past year. The decision is now a simple one of getting the most 'bang for the buck.'

The next issue for a new operator of an azimuthing thruster tug is the hull construction. Both designs are available for propulsion steered tugs. The tractor configuration is well adapted to perform as a ship assist tug. The tractor tug with Z-Drives is, however, just as limited in versatility as the Voith Water Tractor. Though thrust efficiency is greater, overall efficiency when used for offshore towing, for example, is limited because of the forward position of the thrusters. The tractor tug would also be required to have a diversified towing winch aft for ship assist and offshore towing needs. The only recent building of this design has been by Hvide Marine, with the tug Broward. As with any tractor tug, its performance is based largely on its ability to operate in high speed towing modes (above 6 knots), so the skeg construction and placement of the towing point is very critical.

The reverse tractor design is quickly becoming the common choice for new tug construction in the United States. The versatility and overall performance of this design makes it the ideal choice for an operator who is investing in their first high performance tug. For the purpose of shiphandling, a properly designed reverse tractor tug will be just as effective as a tractor tug with the same horsepower and Z-Drive units. Both tugs are highly maneuverable and can work easily alongside a ship.

The reverse tractor has several advantages over a tractor tug when working in direct towing modes alongside a ship. The reverse tractor is not required to turn around and work stern into the ship, it works bow on to a ship just as a conventional tug would. This ability eases operator control of the tug. The design of the reverse tractor also places the drive units further away from the hull of the ship so that interaction between the drive units and water flow along the ships hull is minimized. This is very useful when thrusting away from the ship, as when pulling a ship away from a pier. It should be noted, however, that one distinct advantage the tractor configuration has over the reverse tractor is the ability to run ahead of the ship to put up a towline to the bow. The reverse tractor tug would have to run astern to perform this task, or come alongside the ship very near the bow. The latter maneuver puts the tug at risk of being caught under the ship's bow, similar to the Fairplay I tragedy. (See Fig. 12 and Fig. 13).

When considering high speed ship towing operations, the reverse tractor is at a disadvantage unless properly designed to perform functions such as indirect towing. The reverse tractor hull must be properly designed so that it is capable of producing the hydrodynamic forces necessary to balance the towline forces and the thrust produced by the drive units. The addition of the box keel has been proven to increase the hydrodynamic drag, and thus the bollard pull applied to the towline when working in the indirect mode. Tank trial simulations conducted by Aquamaster-Rauma found that the addition of a box keel to a reverse tractor tug's hull increased effective bollard pull by over 40%.[119]

The reverse tractor design is also well suited to dedicated barge work and offshore towing; several tugs have been built on the West Coast strictly for this purpose. The reverse tractor has been found to work well towing astern and alongside. The addition of a heavy towing winch aft can also prove to be a great asset for a reverse tractor designed as a ship assist tug. One of the first contracted jobs for the Kinsman Eagle II (Kinsman Hawk Class), owned by Bay Transportation, was to assist in towing an oil rig in the Gulf of Mexico. This reverse tractor tug was built with escort work as its primary mission, but served well when used in an offshore towing operation.

Thus, the reverse tractor tug fitted with azimuth rotateable thrusters is the logical and economical

Thus, the reverse tractor tug fitted with azimuth rotateable thrusters is the logical and economical choice for a towing company which is investing in new technology to increase its market share. The venture into a new service can make or break the provider. This tug design limits the possibility of a poor investment by being diversified in its capabilities, as well as being able to perform at a high level of competition among other tug configurations.

Update

At this time, the possibility of an advanced tug such as a tractor or reverse tractor entering service in Charleston Harbor is growing. When this analysis was begun in January of 1996, the idea was not well received. In the spring of that year, trial simulations were conducted at the Waterways Experimental Station utilizing a computer simulated specialized tug operating in the indirect mode on the stern of a ship passing through the Hog Island - Drum Island Reaches and into Myers Bend. It was not possible to obtain written results and plots of these trials because the study was funded by the South Carolina State Ports Authority, as opposed to the Army Corps of Engineers. From discussions with local bar pilots and docking masters the results were very positive. In August of 1996 the Kinsman Eagle II was contracted to work for White Stack Maritime, one of the two ship assist companies operating in Charleston, for a trial period of several weeks. During that time the 6700 horsepower reverse tractor tug was used to assist Evergreen "R" class container ships, which are 942 feet in length, when transiting the Hog Island - Drum Island Reach and Myers Bend. The results of this live trial were directly in line with the hypothesis of this study. In a discussion of the live trial with Captain West, he said that the Kinsman Eagle II "exceeded expectations" in its performance when used in the indirect mode to help turn the ship and when used in the transverse arrest mode to slow the ship.

The trial began just south of the Highway 17 bridges, in Hog Island Reach, where the tug put up its line to the stern of the inbound ship. At this point the speed over the ground was approximately 8 to 8.5 knots and speed through the water with the ebb current was at times as high as 10 knots through the water. The Kinsman Eagle II was used to first swing the ship's stern to starboard, entering Drum Island Reach, and then to swing the stern to port when entering Myers Bend. During this trial significantly less rudder was used than normally required to navigate the turns. A second test was also conducted to determine the ability of the tug to slow the advance of a ship. The Kinsman Eagle II was ordered to slow the ship from a speed of about 7.5 knots. By using the transverse arrest and direct arrest modes, the ship's speed was reduced from 7.5 knots to 4.5 knots in about 3 minutes. It was determined that approximately 200,000 lbs of line pull would be required for these operations on similar sized ships. This produced force would account for other conditions such as adverse wind as well. Thus, a tug of similar construction to the Kinsman Hawk class would provide "a cushion or safety factor" according to Captain West.[120]

Since the trial tests were conducted there has been little public advance toward permanently establishing a tractor or reverse tractor tug in Charleston. The use of such a tug is too much a factor of economics. The selection of a tug must be profitable and applicable to the customer. Therefore, the safest option for a port, where the possibility of a grounding or collision is a growing threat with increased vessel traffic rates, becomes secondary.

Fig. 46. The proposed location of a new terminal is on the eastern side of Daniel Island. The land was originally to be undeveloped as part of a town planning structure for Daniel Island.[121]

The newest change to influence the port is the purchase of the eastern side of Daniel Island, adjacent to the area of the already planned terminal mentioned in the Port Analysis section of this study. The construction of this terminal would add as many as five new berths on the Wando River side of Daniel Island. This location has long been advocated as the safest location, as far as shiphandling is concerned, for new terminal construction. The approach to the terminal involves no major bends in the channel and is accessible at all stages of the tide. A turning basin is already in place adjacent to the Wando/Welch Terminal. Thus, the use of this terminal will allow the larger container ships calling on the port to have a straight run to the berth.

The decision to place this terminal in the proposed location should have little impact on a tug

The decision to place this terminal in the proposed location should have little impact on a tug companies' decision to invest in a tractor or reverse tractor tug however. Several years will pass before ground is broken for the construction of these new terminals. The decision to build a tractor or reverse tractor tug for service in Charleston may be delayed, but the need for improved equipment is going to continue to grow just as the size and number of vessels calling on the port grows. An interim solution may be provided by chartering a tug temporarily from a company such as Bay Transportation for example. This would allow the tug operating the new tug to introduce a new service to the shipping companies and agents who order the tugs and win their acceptance. This would also allow the company to determine appropriate rate changes that would be necessary for the successful implementation of such an investment.

The selection of a reverse tractor tug equipped with azimuth rotateable drives is the most practical choice for the first step of modernizing the existing fleet of ship assist tugs in Charleston. Having stated this, many would agree, but say the issue still remains one of cost. The best answer available for that rebuttal is that the port as a whole must look to the future. Charleston is quickly becoming the largest port on the East Coast. The tug companies, as well as other port oriented industries, must examine their services and ensure that the services they provide now will continue to have the same value five or even ten years into the future. Safety and efficiency is the primary goal of the Port of Charleston; to place an advanced tug, as discussed above, into service in Charleston Harbor would enhance both of these values. The modern propulsion steered tug represents a huge investment with the possibility of unlimited returns. Now is the time to commit to this present solution, instead of waiting until it is too late to correct the problem.

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